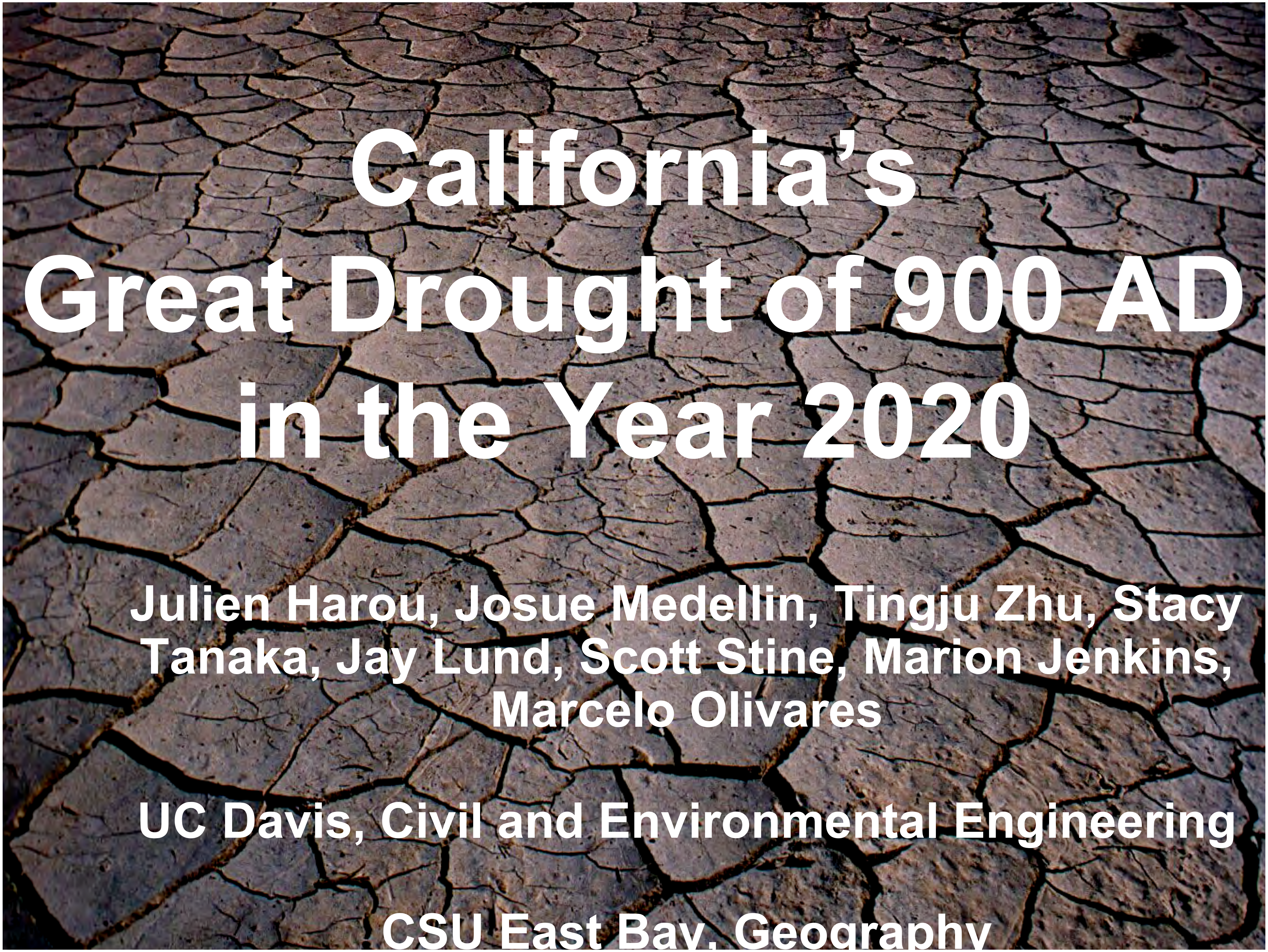

California's Great Drought of 900 AD in the Year 2020

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100+yr. Droughts in California?

"Here I present a study of relict tree stumps rooted in present-day lakes, marshes and streams, which suggests that California's Sierra Nevada experienced extremely severe drought conditions for more than 2 centuries before AD~1112 and for more than 140 years before AD~1350."

"Future natural or anthropogenically induced warming may cause a recurrence of the extreme drought conditions"

"California's mediaeval precipitation regime, if it recurred with today's burgeoning human population, would be highly disruptive environmentally and economically."

(ref. Scott Stine, *Nature*, June 1994)

Objective

Estimate effects of extreme severe and sustained drought in California on:

- Water scarcity
- Regional economic costs due to scarcity
- Local willingness to pay for additional water
- Economic value of capacity expansion, water transfers and conjunctive use operations
- Environmental flows and opportunity costs

Presentation Outline

- Method: CALVIN model
- Paleodrought
- Synthetic drought hydrology
- Model Results
- Discussion, limitations and conclusions

CALVIN, Economic-Engineering Model of California Water Supply

- Minimizes economic costs subject to constraints:
  - Economic values for agricultural, urban, & hydropower uses
  - Operating costs: water treatment, pumping, etc.
  - Flow environmental constraints
  - Uses HEC-PRM optimization code
- Prescribes water operations and allocations over a 72-year hydrology.
- Surface and groundwater resources represented.
- Supplies and demands represented (economically).
- Study uses year 2020 projected demands and infrastructure.

http://cee.engr.ucdavis.edu/faculty/lund/CALVIN/

Economic-Engineering Optimization: CALVIN

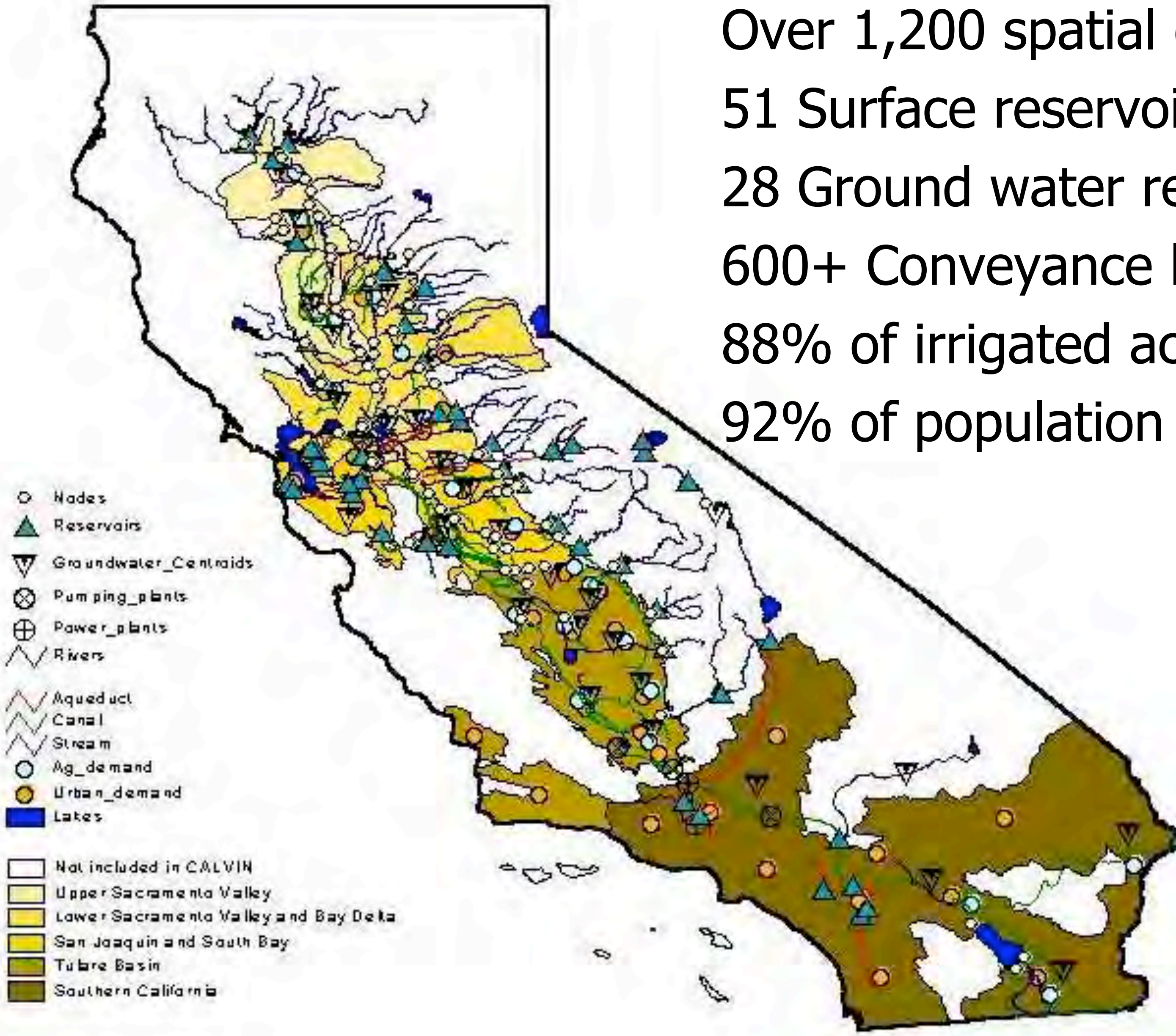
- Surface and ground water hydrology
- Facilities & capacities
- Environmental flow constraints
- Urban values of water
- Agricultural values of water
- Operating costs

CALVIN Economic Optimization Model:

Databases of Input & Meta-Data	HECPRM Solution Model

- Economic benefits
- Conjunctive use & cooperative operations
- Willingness-to-pay for water and reliability
- Water operations & delivery reliabilities
- Value of flexible operations
- Values of increased capacities

CALVIN Model Coverage

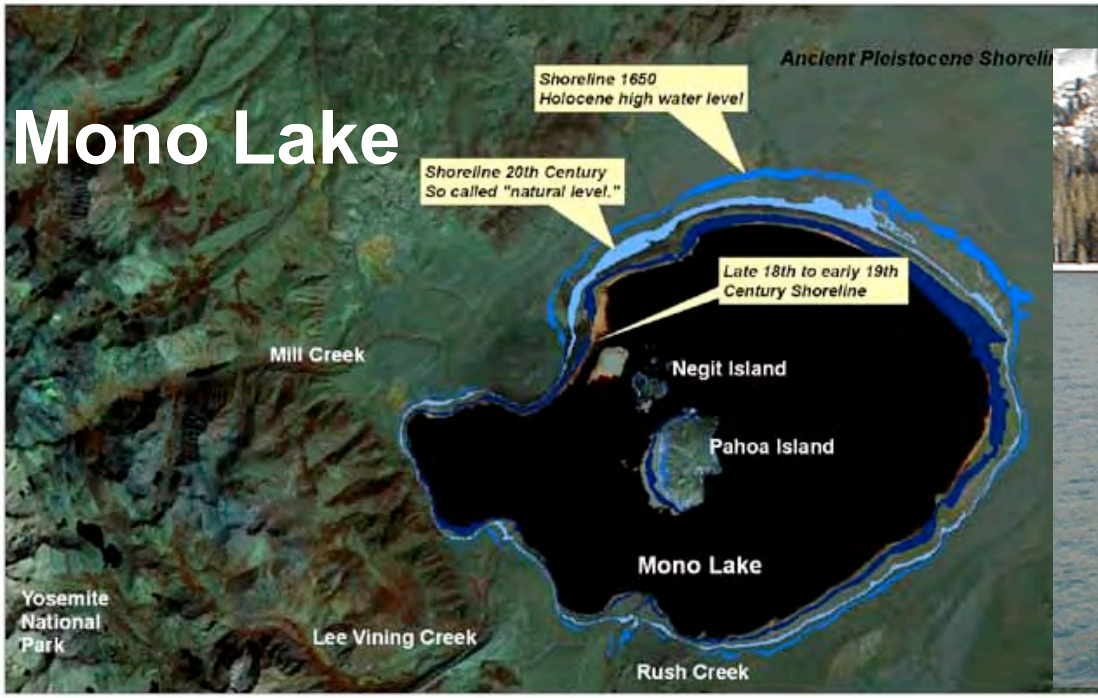


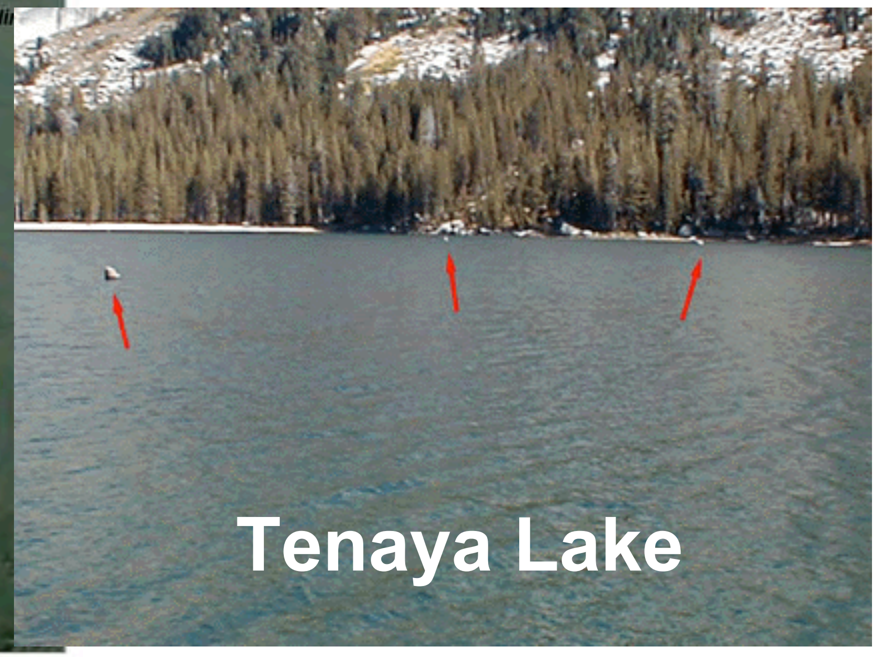
Over 1,200 spatial elements
51 Surface reservoirs
28 Ground water reservoirs
600+ Conveyance links
88% of irrigated acreage
92% of population

Paleodrought Hydrology

- Scott Stine (1986 - 1994)
- Severe and sustained droughts enough to reduce inflows to Mono Lake (hydrographically closed lake) by 40-60% for ~100 years (tree-ring records with carbon dating).
- No period within the droughts wet enough to raise the lake level enough to inundate and drown these trees.
- Droughts not unique to Mono Basin. All along the Sierra Nevada range are indications of sustained drought during these same periods.

Paleodrought Hydrology

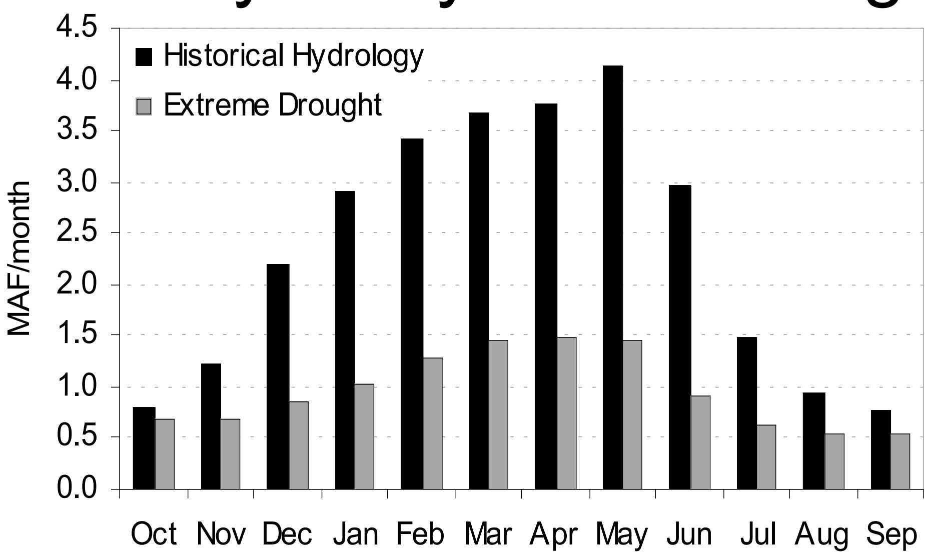


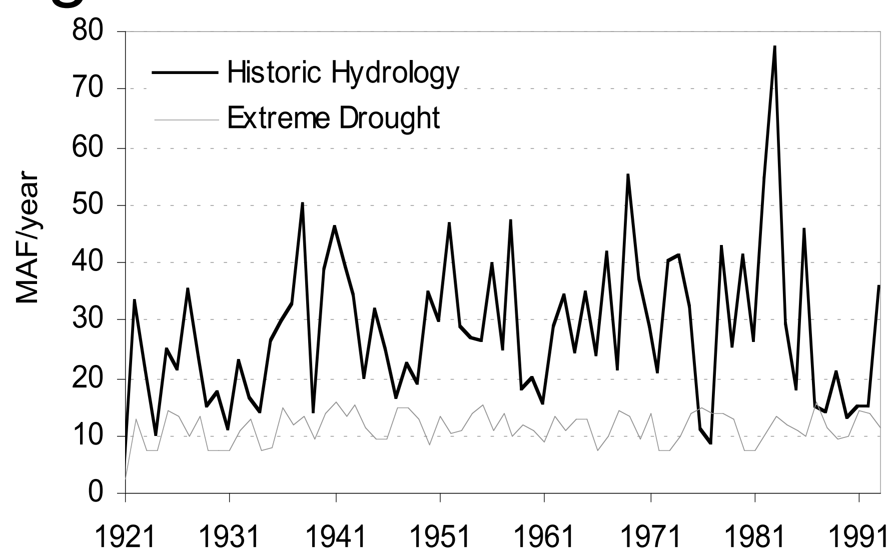


West Walker River

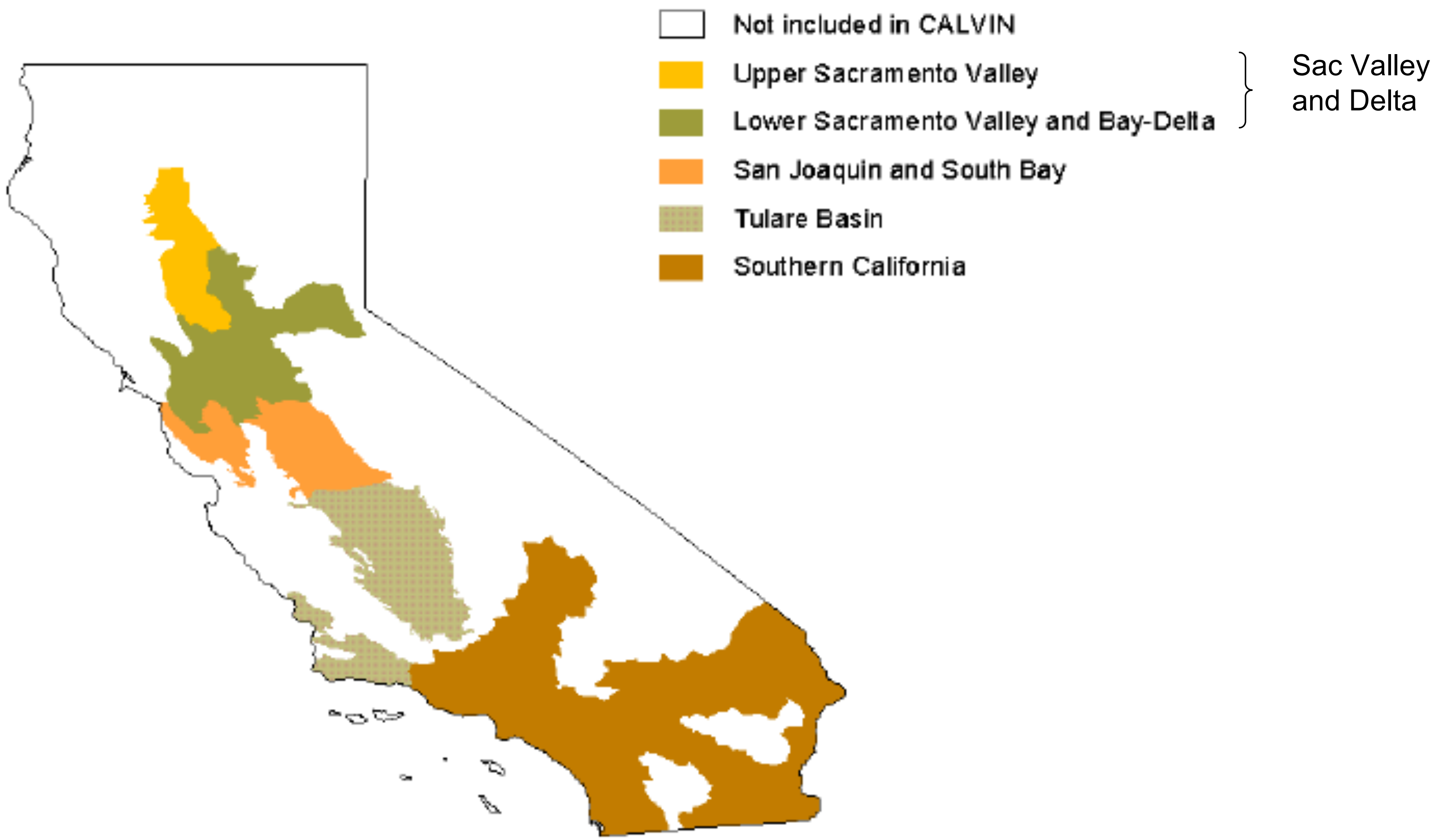
Synthetic Paleodrought Hydrology

- Random re-sampling from 10 driest years of record since there is evidence that there were no "wet" years in paleodrought(s).
- Re-sampling method produces time series of surface water inflows, groundwater inflows, local accretions (intra-basin runoff), seepage losses in rivers and environmental minimum flows.
- 72-year synthetic drought generated.





Spatial Aggregation of Model Results



Model Runs

Three model runs:

1. Base Case – constrained to operations and deliveries with 1997 policies, historical hydrology, 2020 water demands.

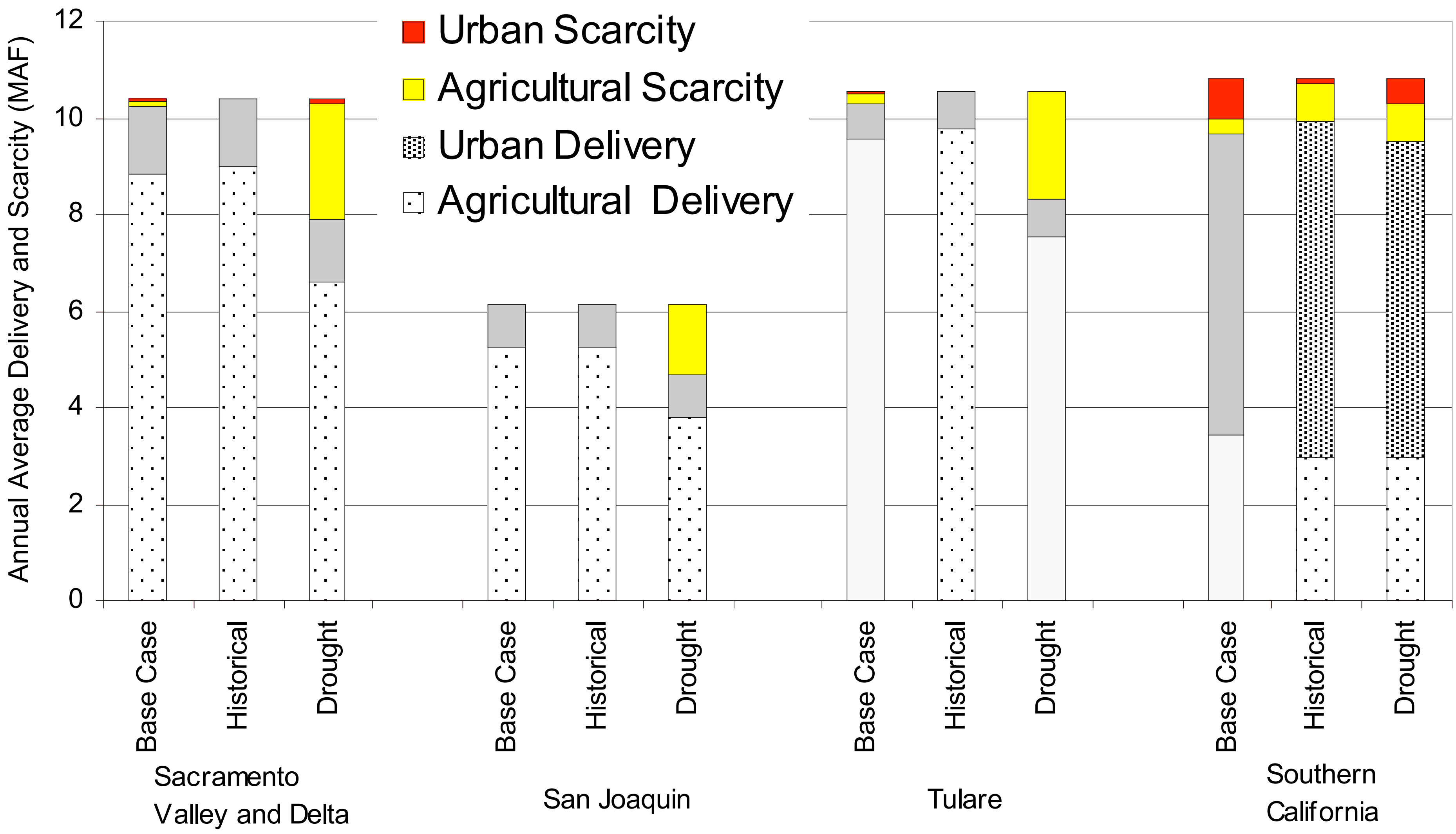
2. Optimized Historical Hydrology – 2020 water demands.

3. Optimized Extreme Drought – 2020 water demands.

Water Scarcity Results

	Delivery Target	Scarcity (%)		
		Base Case	Historical	Drought
Urban and Ag				
Sac. Valley and Delta	10,379	2%	0%	24%
San Joaquin Valley	6,153	0%	0%	24%
Tulare Basin	10,553	3%	0%	21%
Southern California	10,816	10%	8%	12%
Total	37,901	4%	2%	20%
Agriculture Only				
Sac. Valley and Delta	9,005	2%	0%	27%
San Joaquin Valley	5,259	0%	0%	28%
Tulare Basin	9,773	2%	0%	23%
Southern California	3,716	8%	20%	20%
Total Agriculture	27,754	2%	3%	25%
Urban Only				
Sac. Valley and Delta	1,374	1%	0%	6%
San Joaquin Valley	894	2%	0%	0%
Tulare Basin	779	5%	0%	0%
Southern California	7,099	12%	2%	7%
Total Urban	10,147	9%	1%	6%

Scarcity & Delivery Results



Scarcity Cost Results ($M/yr)

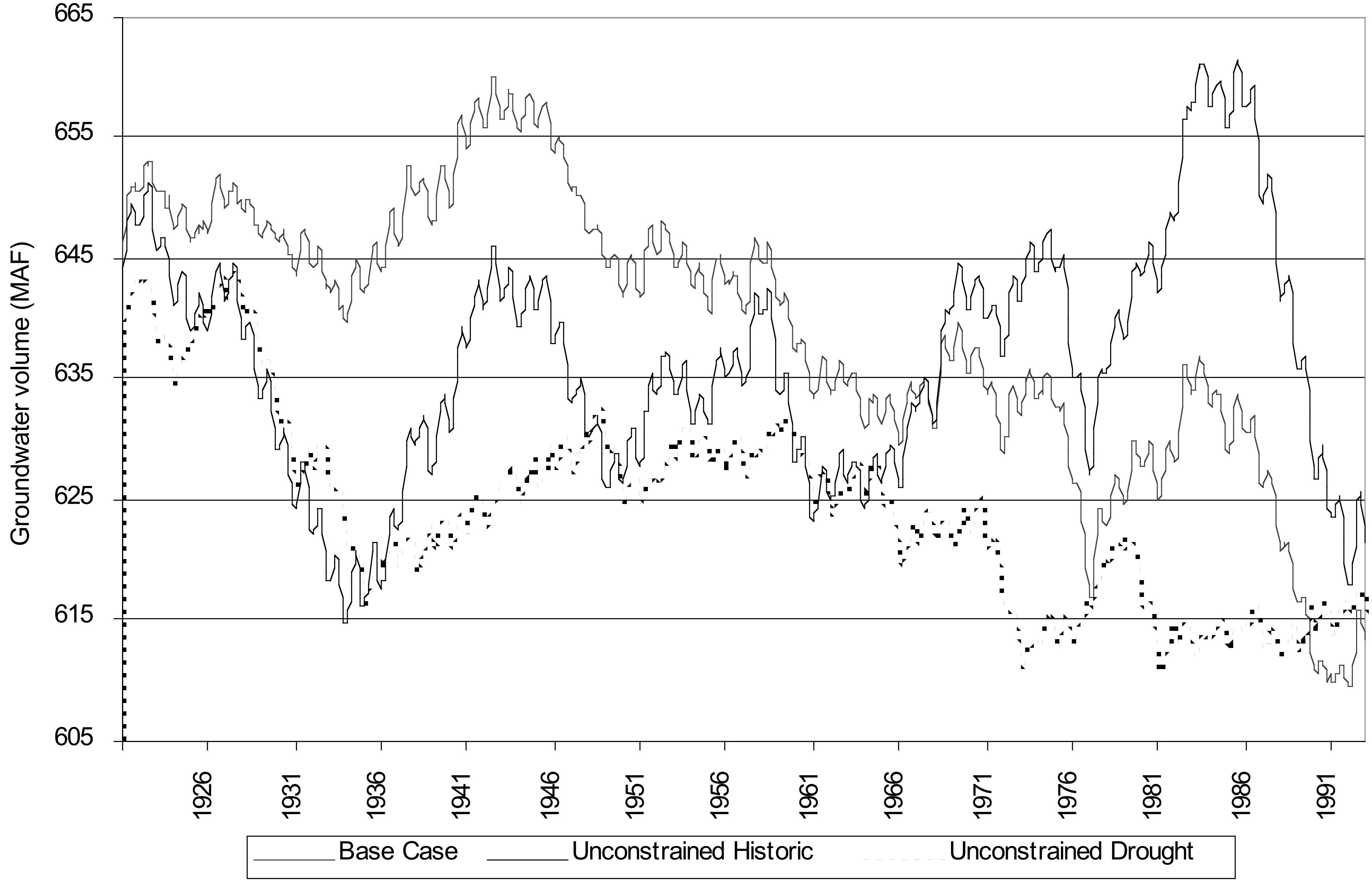
	Base Case	Optimized Historical	Optimized Drought
Urban and Ag.			
Sac. Valley and Delta	42.3	0.6	468.5
San Joaquin Valley	15.3	0.1	256.0
Tulare Basin	36.8	0.5	480.5
Southern California	1,501.3	121.3	472.0
Total	1,596	123	1,677
Agriculture Only			
Sac. Valley and Delta	6.8	0	271.6
San Joaquin Valley	0.2	0.1	256.0
Tulare Basin	0.0	0.5	480.1
Southern California	19.1	32.5	32.5
Total Agriculture	6	33	1,040
Urban Only			
Sac. Valley and Delta	35.5	0.6	196.9
San Joaquin Valley	15.3	0	0.1
Tulare Basin	17.7	0	0.4
Southern California	1,495.6	88.8	439.4
Total Urban	1,564	89	637

Operating Costs Results

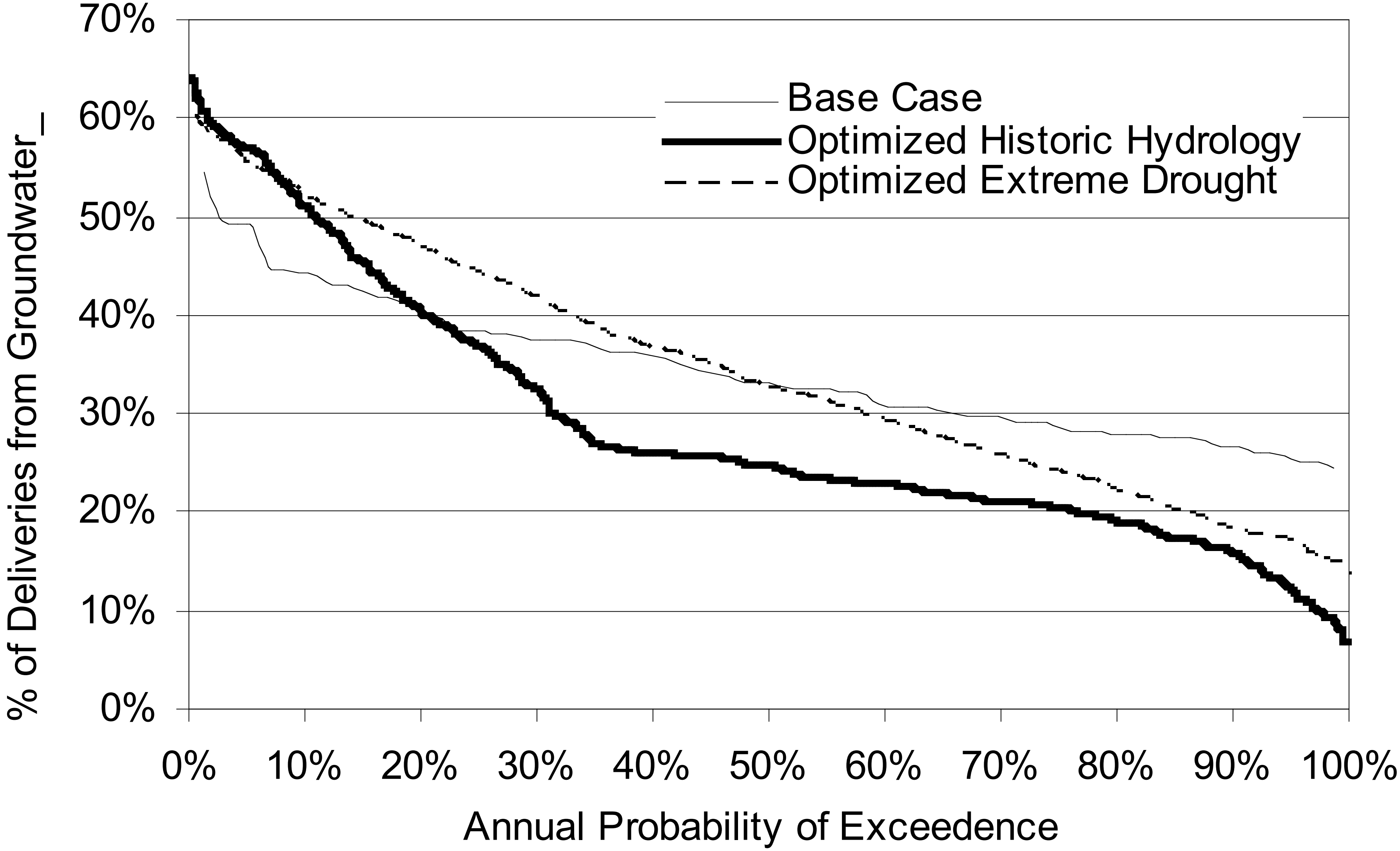
	Operating Costs ($M/yr)		
Scenario:	Base Case	Historical	Drought
Sacramento	247	200	182
San Joaquin	394	375	378
Tulare	461	920	936
Southern Cal.	3,074	1,974	1,901
Total	4,176	3,468	3,396

	Average Unit Operating Costs ($/AF)		
Scenario:	Base Case	Historical	Drought
Sacramento	24	19	23
San Joaquin	64	61	81
Tulare	45	87	113
Southern Cal.	317	199	199

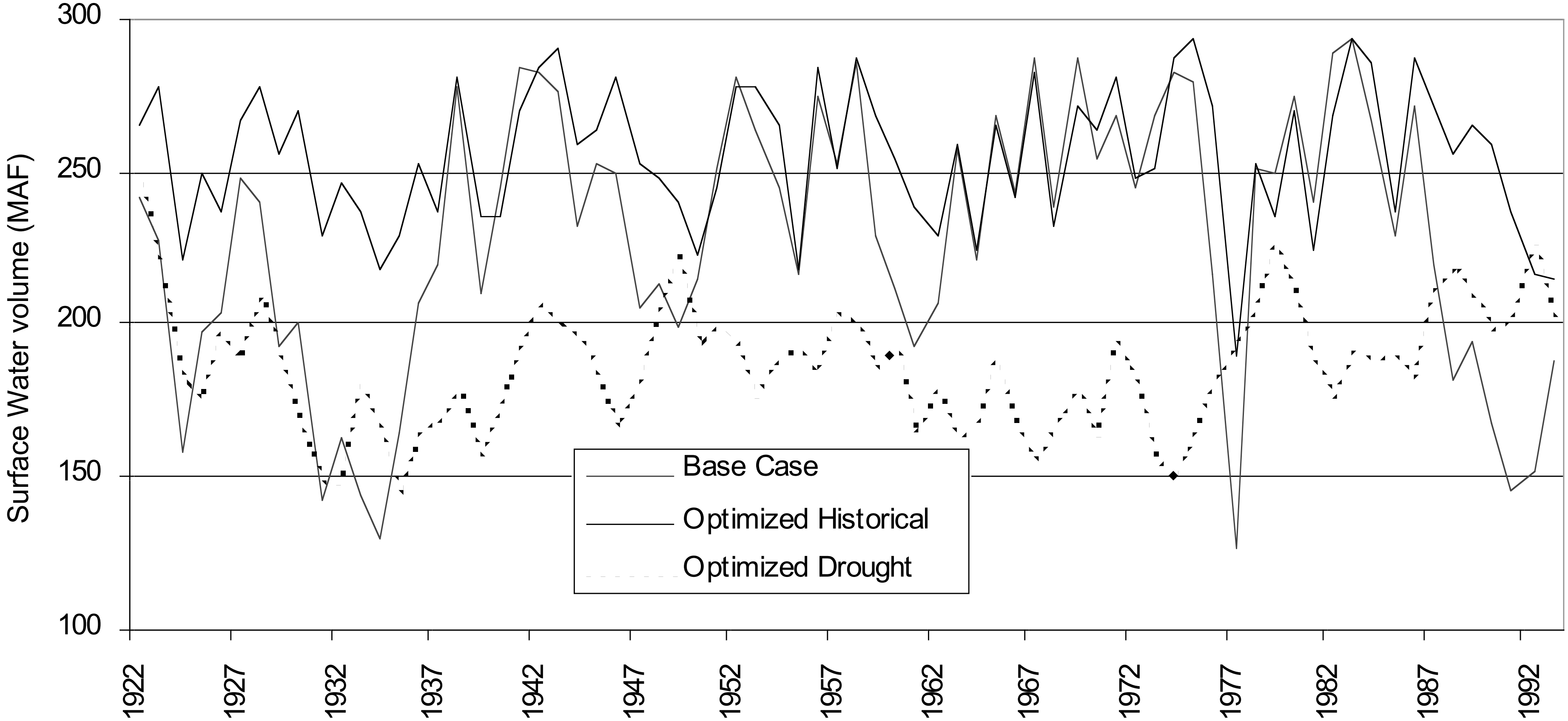
Monthly Groundwater Storage



Annual Groundwater Use Variability



Annual Surface Water Storage



Marginal Value of More Water (WTP)

	Maximum Marginal WTP ($/AF)		
	Base Case	Optimized Historical	Optimized Drought
Urban and Ag.			
Sac. Valley and Delta	285	28	2,443
San Joaquin Valley	236	1	200
Tulare Basin	383	18	220
Southern California	8,512	1,020	985
Agriculture Only			
Sac. Valley and Delta	34	0	127
San Joaquin Valley	0	1	200
Tulare Basin	131	18	220
Southern California	19	75	74
Urban Only			
Sac. Valley and Delta	285	28	2,443
San Joaquin Valley	236	0	7
Tulare Basin	383	0	65
Southern California	8,512	1,020	985

Environmental Flow Opportunity Costs ($/AF)

	Average Opportunity Cost		Maximum Opportunity Cost	
	Historical	Drought	Historical	Drought
Minimum Instream Flows				
Trinity River	34	50,302	58	140,801
Clear Creek	17	49,515	35	140,670
Sacramento River	0.2	353	7	140,145
Sacramento River at Keswick	2	39,765	20	139,567
Feather River	0.3	55	9	199
American River	0.5	76	10	1,043
Mokelumne River	2	2,180	9	3,459
Calaveras River	0	6	0	297
Yuba River	0	83	7	4,098
Stanislaus River	9	131	45	336
Tuolumne River	8	151	39	455
Merced River	9	86	28	339
Mono Lake Inflows	963	474	1428	2,381
Owens Lake Dust Mitigation	745	1,109	814	1,868
Refuges				
SacWestRefuge	3	172	9	919
SacEastRefuge	0.2	4	6	184
Volta Refuges	24	180	31	329
San Joaquin/Mendota Refuges	21	142	29	259
Pixley	32	315	48	405
Kern	38	204	46	285
Delta Outflow				
Delta	2	100	8.3	210

Avg. Marginal Value of Conveyance Capacity ($/AF/year)

	Historical	Drought
Colorado Aqueduct	1,739	3,321
Kings River Diversion	47	690
Sacramento River Diversion	0	609
American River Diversion	0	595
Cross Valley Canal	0	378
Kern Water Bank Canal	0	295
Auld Valley Pipeline	0	74
Arvin Eddison intertie	0	70
SFPUC to Santa Clara Valley	0	41
Auld Valley Pipeline	18	0
San Diego Canal	5	0
Santa Ana Pipeline	3	0
MWD Feeders	0	1

Limitations/Assumptions

- Re-sampling approach produces no single year drier than the driest year on historical record.
- Colorado River supplies not reduced beyond current 4.4 million acre-feet.
- Optimization approach assumes California management institutions can be very adaptive.

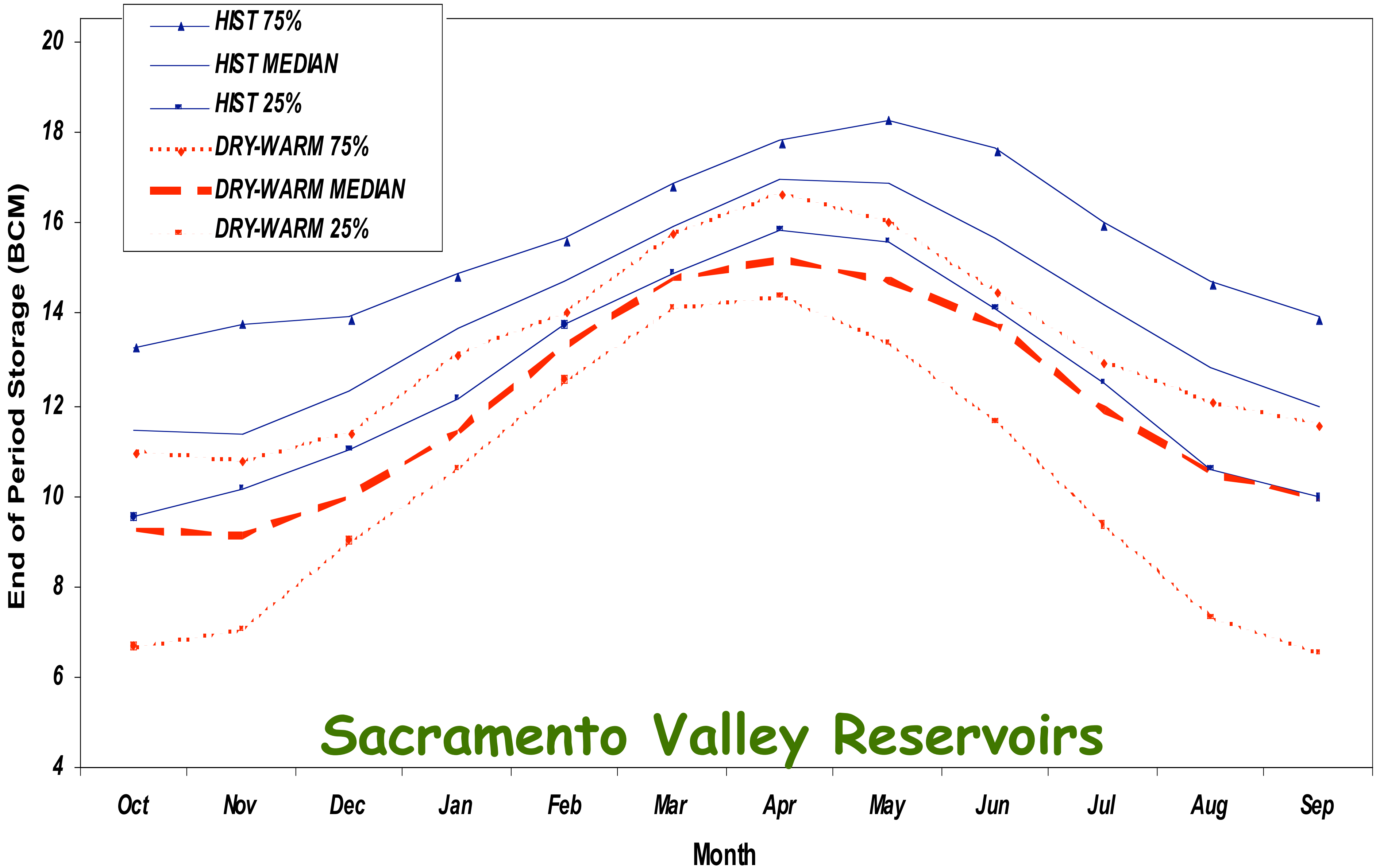
Conclusions

- Preliminary look at California's water supply system's ability to adapt to severe, prolonged drought.
- Drought was a synthesized version of two droughts from recent geologic record.
- Severe regional economic & water supply effects for agriculture.
- Due to flexible reallocation, overall statewide water supply *system and* economy *could continue to function without a catastrophe.*
- To respond to such a severe and prolonged drought would *require considerable institutional flexibility*.

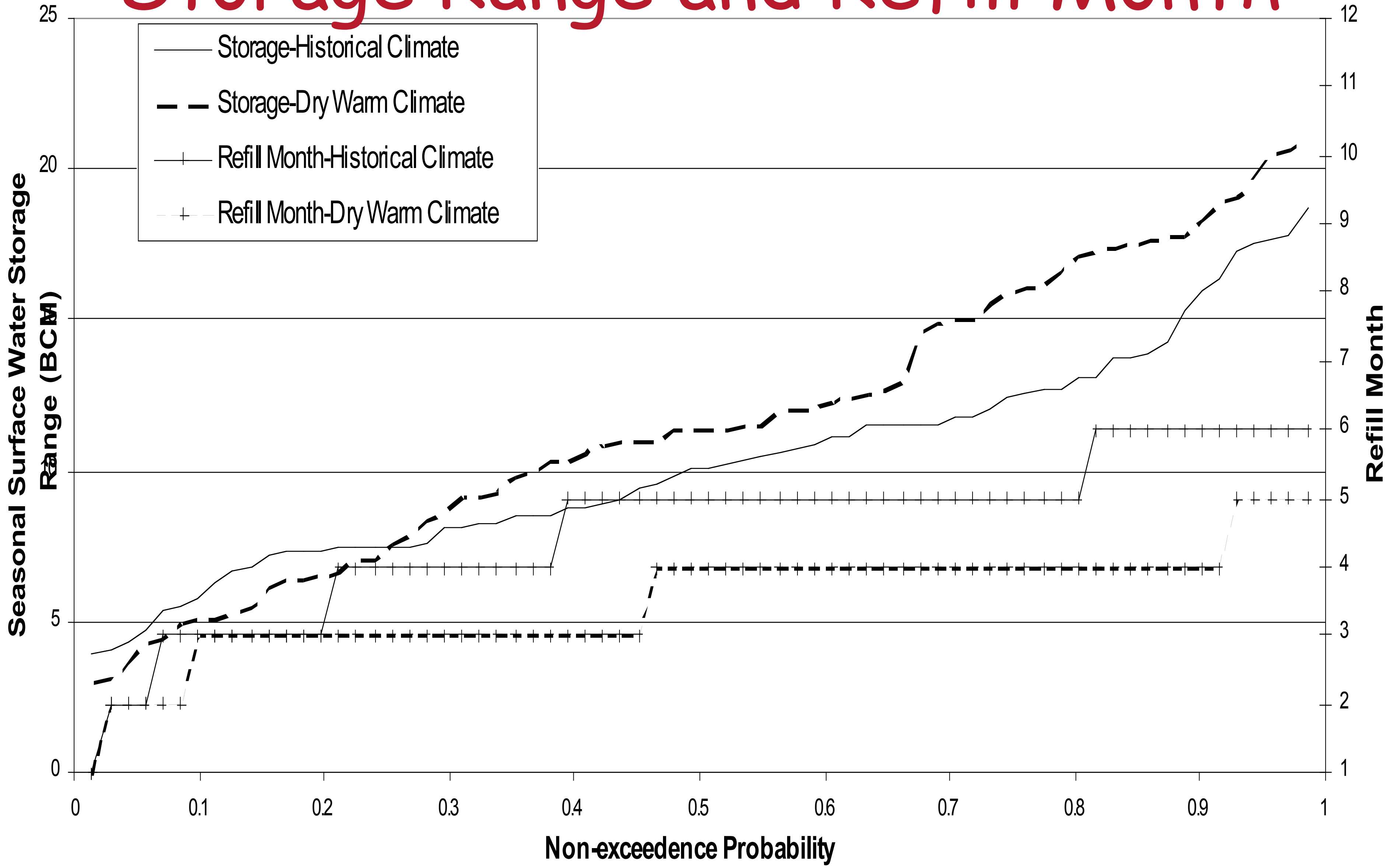
Operations and Climate Warming

- ✓ How would climate change affect optimal reservoir operating policies?
- ✓ Use optimization model (CALVIN) results to compare optimal operating policies with and without a climate change.
- ✓ CALVIN is an economically-driven optimization model of California's water supply system.
- ✓ What can we learn from optimization model results?

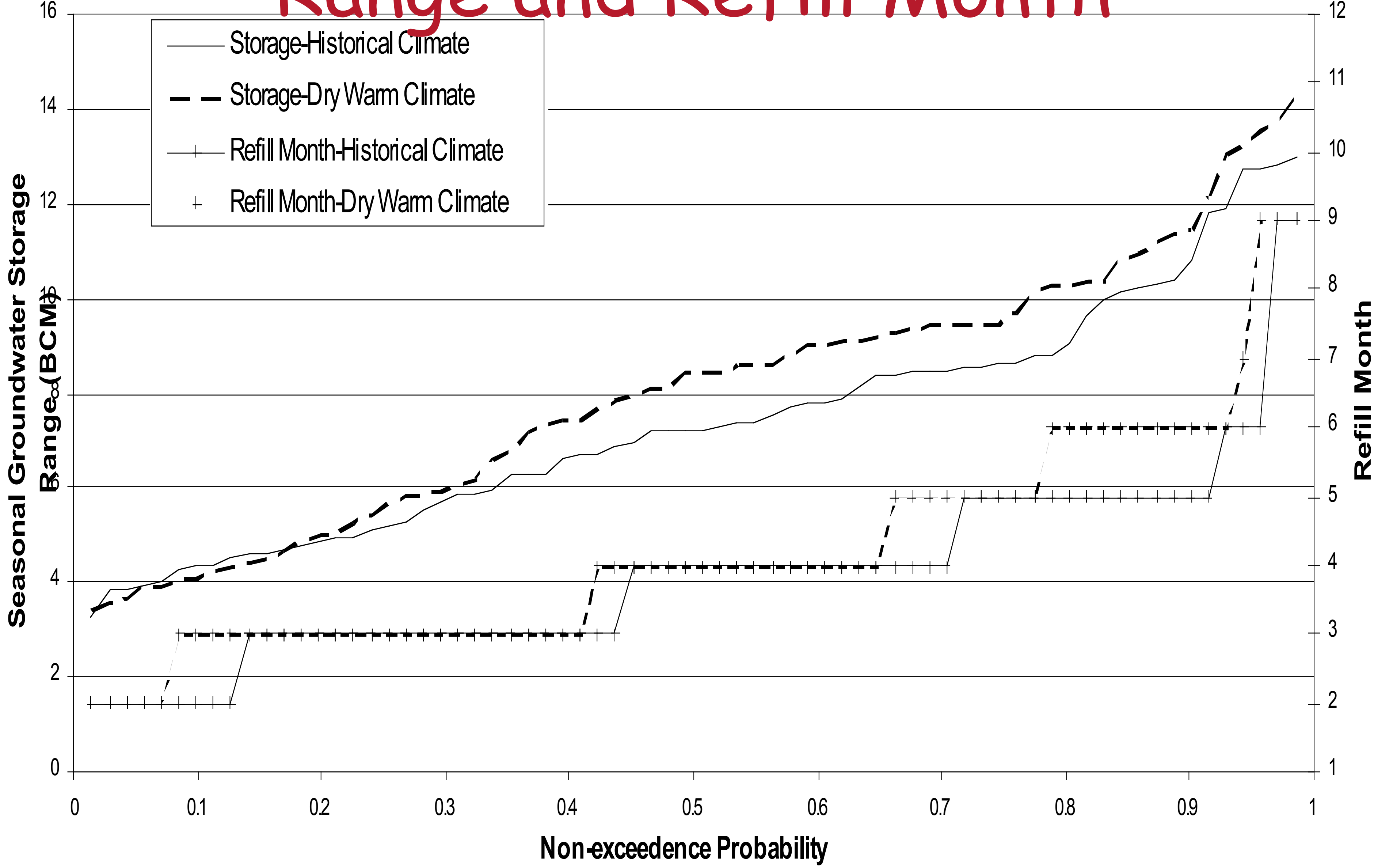
Monthly Reservoir Storage



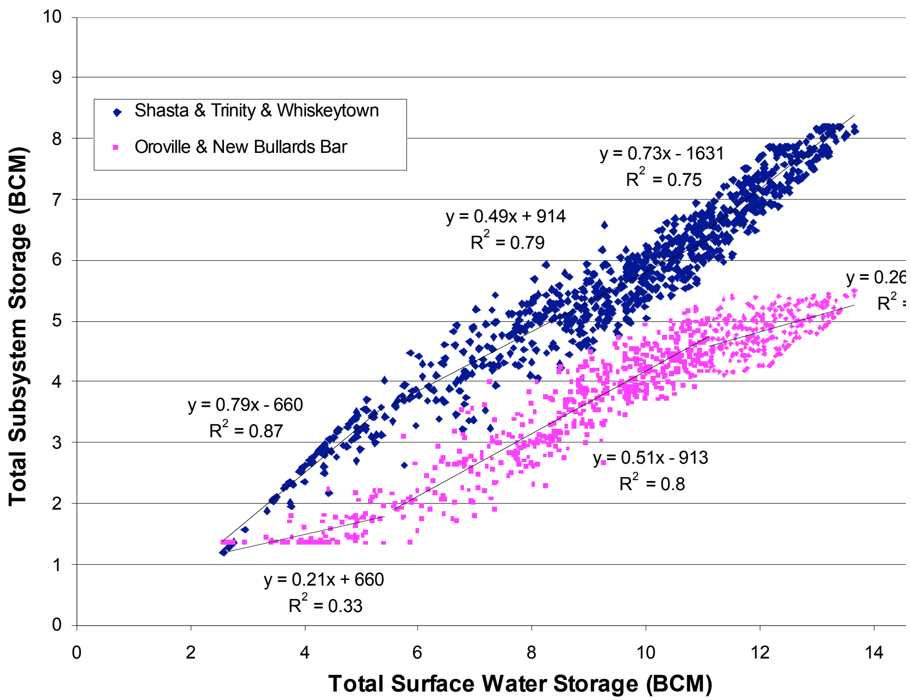
Surface Water Seasonal Storage Range and Refill Month



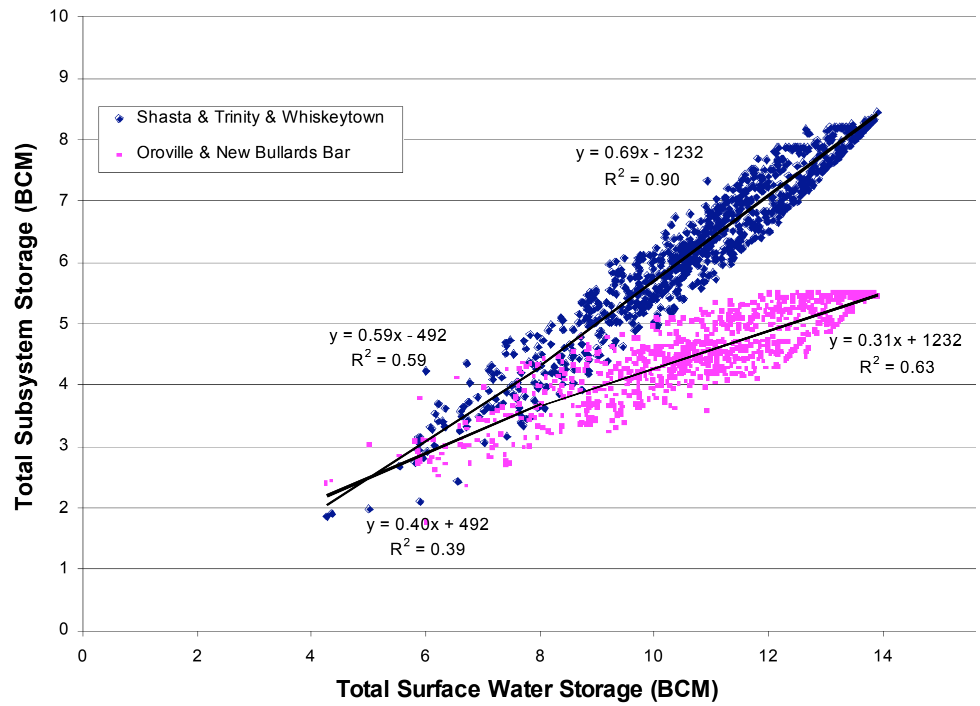
Groundwater Seasonal Storage Range and Refill Month



Surface Storage Balancing Rules (Northern California)



Historic Climate



Dry-Warm Climate Change

Res. Op. Findings & Insights

- ✓ Optimal reservoir operating rules change with climatic conditions. Old operating rules are unlikely to do well for future conditions.
- ✓ Groundwater and conjunctive use have significant water supply roles in California for either climate.
- ✓ Climate warming results in an earlier refill of surface water reservoirs with optimized operations.
- ✓ Dry climate warming increases the optimal amplitude of the seasonal draw-down refill cycle.
- ✓ The optimal allocation of storage among surface water reservoirs changes significantly with climate.